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14. ABSTRACT

We are in the second year of a three-year project to generate in modern form an easily usable archive of digital seismograms derived from regional waveforms recorded at the Borovoye Observatory (BRV), northern Kazakhstan, over a thirty-year period going back to 1966 and spanning the time when state-of-the-art sensors and dataloggers were introduced at this site by several different western groups. The BRV seismograms, which include multichannel regional signals from 350 underground nuclear test explosions carried out in Eurasia, were made generally available to western scientists in 2001, but only as copies of the bits in the original digital waveforms. These copies contain large numbers of glitches and did not include instrument responses for approximately two-thirds of the events. In the first two years of this project, we are focusing on basic processing of the damaged waveforms to make them more easily usable by the removal of glitches and the inclusion of instrument responses (including absolute gains as well as poles and zeroes). In the third year we shall focus on a series of research projects with the restored waveforms. Our project is a joint effort by scientists at Lamont-Doherty Earth Observatory of Columbia University (LDEO) and at Los Alamos National Laboratory (LANL). Three different sets of Soviet-style instruments and recording systems were used at BRV from 1966 to 1996. LANL scientists first processed the BRV regional signals for 210 nuclear tests (1,355 traces), mainly those for which instrument responses were available (the TSG system). In this project, LANL has also now processed the waveforms of the so-called SS system for 148 nuclear tests (1,215 traces), some of which were also recorded on the TSG system; and in late June 2008, LANL completed processing for waveforms in the archive from the SS and TSG systems (474 and 281 traces, respectively). A remaining main block of events, recorded on the KOD system (which was used in operations beginning in 1966 and operated continuously from 1967 to 1973) is planned for processing this year. The KOD system, which is based on three-component, short-period seismometers, is important as one of the few digital systems anywhere in the world in the late 1960s and early 1970s. As part of the process of quality assurance, we are making measurements of signal amplitude where possible from the restored waveforms, to see if relative amplitudes of different parts of the seismogram (P, Lg, Rg, longer period surface waves, coda) meet expectations. We are also interpreting absolute amplitudes, for those underground nuclear explosions at the Semipalatinsk Test Site (STS), and in the Soviet Union's Peaceful Nuclear Explosion program, for which yield information is available. Although only 27 underground nuclear tests at the STS have officially announced yields (Mikhailov, 1996), additional yield information has been supplied in a variety of publications, and we have 62 STS underground nuclear tests for which yields have been reported.

15. SUBJECT TERMS
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IMPROVEMENTS TO A MAJOR DIGITAL ARCHIVE OF SEISMIC WAVEFORMS FROM NUCLEAR EXPLOSIONS: BOROVOYE SEISMOGRAM ARCHIVE

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ABSTRACT

We are in the second year of a three-year project to generate in modern form an easily usable archive of digital seismograms derived from regional waveforms recorded at the Borovoye Observatory (BRV), northern Kazakhstan, over a thirty-year period going back to 1966 and spanning the time when state-of-the-art sensors and dataloggers were introduced at this site by several different western groups. The BRV seismograms, which include multi-channel regional signals from 350 underground nuclear test explosions carried out in Eurasia, were made generally available to western scientists in 2001, but only as copies of the bits in the original digital waveforms. These copies contain large numbers of glitches and did not include instrument responses for approximately two-thirds of the events. In the first two years of this project, we are focusing on basic processing of the damaged waveforms to make them more easily usable by the removal of glitches and the inclusion of instrument responses (including absolute gains as well as poles and zeroes). In the third year we shall focus on a series of research projects with the restored waveforms. Our project is a joint effort by scientists at Lamont-Doherty Earth Observatory of Columbia University (LDEO) and at Los Alamos National Laboratory (LANL).

Three different sets of Soviet-style instruments and recording systems were used at BRV from 1966 to 1996. LANL scientists first processed the BRV regional signals for 210 nuclear tests (1,355 traces), mainly those for which instrument responses were available (the TSG system). In this project, LANL has also now processed the waveforms of the so-called SS system for 148 nuclear tests (1,215 traces), some of which were also recorded on the TSG system; and in late June 2008, LANL completed processing for waveforms in the archive from the SS and TSG systems (474 and 281 traces, respectively). A remaining main block of events, recorded on the KOD system (which was used in operations beginning in 1966 and operated continuously from 1967 to 1973) is planned for processing this year. The KOD system, which is based on three-component, short-period seismometers, is important as one of the few digital systems anywhere in the world in the late 1960s and early 1970s.

As part of the process of quality assurance, we are making measurements of signal amplitude where possible from the restored waveforms, to see if relative amplitudes of different parts of the seismogram (*P*, *Lg*, *Rg*, longer period surface waves, coda) meet expectations. We are also interpreting absolute amplitudes, for those underground nuclear explosions at the Semipalatinsk Test Site (STS), and in the Soviet Union's Peaceful Nuclear Explosion program, for which yield information is available. Although only 27 underground nuclear tests at the STS have officially announced yields (Mikhailov, 1996), additional yield information has been supplied in a variety of publications, and we have 62 STS underground nuclear tests for which yields have been reported.

OBJECTIVES

We propose to generate in modern form an easily usable archive of digital seismograms derived from regional waveforms recorded at the Borovoye Observatory (BRV), northern Kazakstan, over a thirty-year period going back to 1966 and spanning the time when state-of-the-art sensors and dataloggers were introduced at this site in the summer of 1994. Specifically, we expect to process 1,200 to 1,400 digital waveforms from the Borovoye archive, for more than 200 underground nuclear explosions in Eurasia for which digital records are available but not yet in useful form due to problems with glitches and instrument calibration that have not yet been taken into account.

RESEARCH ACCOMPLISHED

Deglitching the Borovoye Archive

During 2007 and spring of 2008, Borovoye Archive waveform data from over 200 underground nuclear explosions have been deglitched by the LANL group. The locations of those explosions are plotted in Figure 1. Deglitched explosions include 73 explosions from Balapan, 59 from Degelen, and four explosions from Murzhik subregions of the STS; eight explosions from Lop Nor Chinese test site, and 53 PNEs (Peaceful Nuclear Explosions).

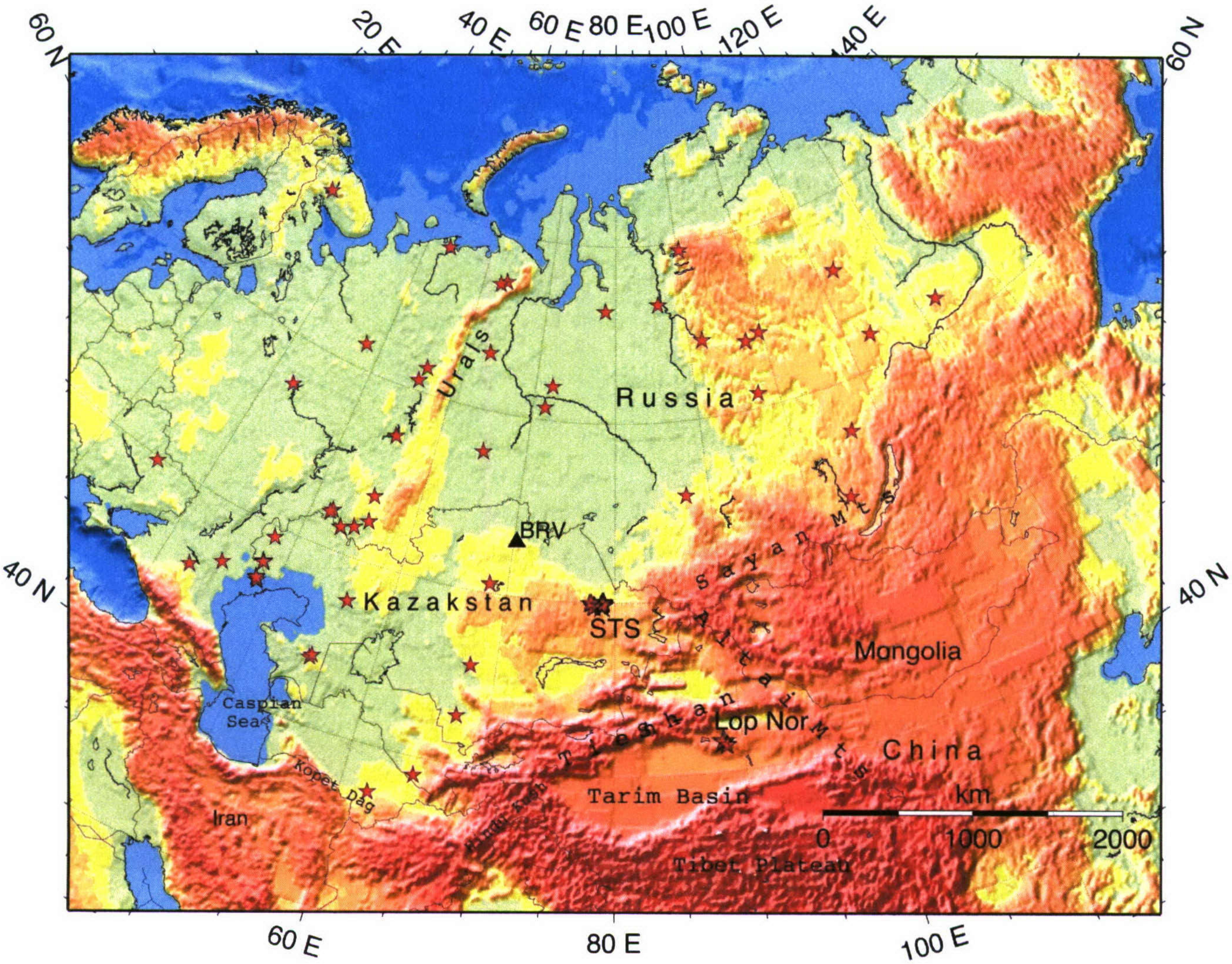

Figure 1. Locations of underground nuclear explosions in Eurasia whose waveform data in the Borovoye Archive had been deglitched in this project by Spring 2008.

An example of an extensive set of deglitched BRV archive seismograms, recorded on two systems (TSG, SS) from an underground nuclear explosion (UNE) at Balapan, on the STS, is plotted in Figure 2. This is a strong explosion with magnitude mb(P) = 6.0 and hence, many channels of the BRV archive records are clipped. The 24-channel STsR-TSG system produced seven useful channels, whereas all 10 channels of the STsR-SS system are useful (see Figure 2). A short-period, vertical-component record of the TSG system, sZ01, which is a low-gain channel with apeak amplitude of 510 counts, is on-scale. Other short-period channels, channels sZ06, sZ07, sN08, sE09 are all clipped. However, these records are still useful for picking accurate arrival times of the first arrival Pn phase (distance 695.6 km), as well as for quantitative analysis of amplitudes using coda waves (e.g., Mayeda and Walter, 1996). This explosion was also recorded by the SS system, which has low-gain long-period channels. Long-period channels, l02Z, l03N, l04E as well as a short-period vertical-component, s06Z are all on-scale. Short-period 3-component channels, s07Z, s08N, and s09E, are all clipped, but their long coda records (24 minutes from the origin time of the explosion), make the records still very useful. For instance, the P wave reflected from core-mantle boundary (PcP, arriving about 420 s after Pn) as well as the P wave reflected from the inner core boundary (PKiKP, arriving about 900 s after Pn) can be identified and used to study the nature of discontinuities in the Earth's deepest interior (e.g., Adushkin et al., 1997).

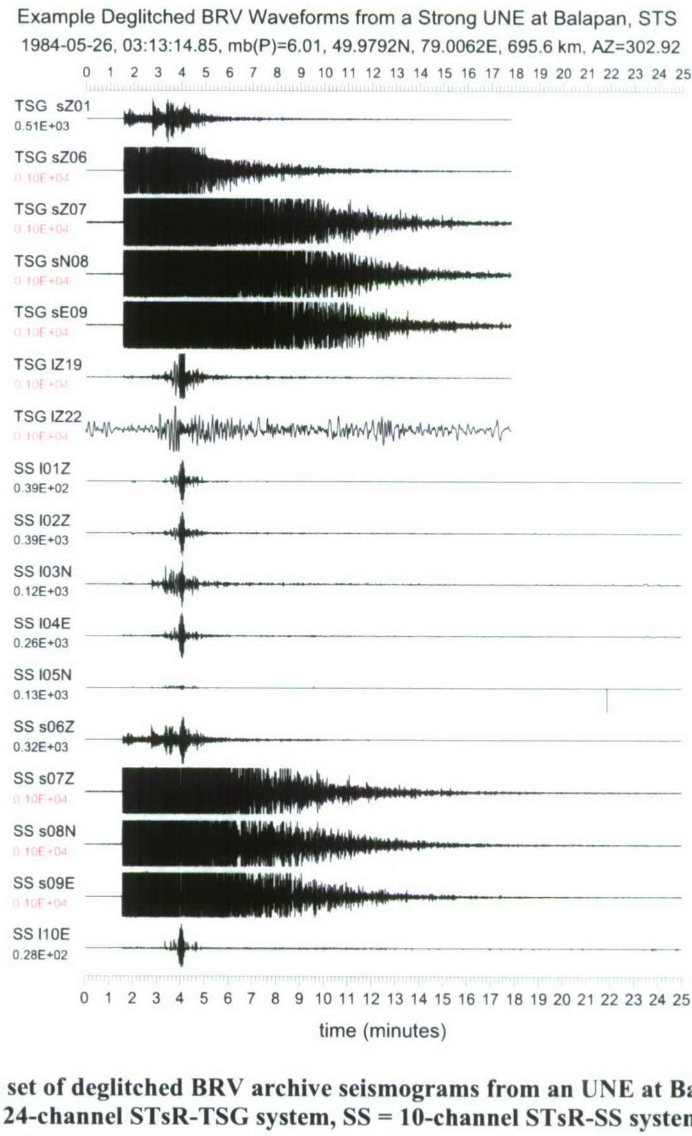

Figure 2. Example of a set of deglitched BRV archive seismograms from an UNE at Balapan, STS. TSG = records from 24-channel STsR-TSG system, SS = 10-channel STsR-SS system. The first letter in the channel names, l or s, indicates long- or short-period records, respectively. The ground motion components (Z, N and E) are indicated by the second letter in the channel names for the TSG system and by the last letter in the SS system.

Calibration of Instrument Response and Gain of Borovoye Archive

We have begun to calibrate instrument responses and gains of the deglitched BRV archive data. We are employing RMS (root-mean-squared) amplitude measurements of P or Lg wave trains to calibrate gains of the instruments used in the BRV archive. For a preliminary study, we have nine unclipped short-period vertical records from the SS system, channel sZ01 (= s01Z), and 28 unclipped short-period vertical records from the TSG system (KSVM, see Adushkin & An, 1990; Kim & Ekström, 1996). Measured RMS values from 37 short-period records from UNEs at Balapan, STS are listed in Table 1 and the first 12 traces are plotted in Figure 3. The KSVM recorder has a nominal gain of 48.6 counts/micron at 1.4 Hz, whereas the SKM-3 recorded in the SS system has a nominal gain of 200 counts/micron at 1.8 Hz (Kim et al., 2001).

Table 1. Measurement of RMS (Lg), and some reported yields, are given here for unclipped short-period digital seismograms in the Borovoye archive from 37 UNEs at Balapan, STS.

Date	Origin Time	Lat. °N	Long.°E	mb(P)	log(RMS)	reported Y (kt)
1975-10-29	04:46:59.82	49.9539	78.8739	5.61	3.04	
1976-04-21	05:02:59.70	49.9006	78.8308	5.12	2.57	
1976-08-28	02:56:59.99	49.9750	78.9264	5.74	3.08	
1976-12-07	04:56:59.85	49.9439	78.8392	5.80	3.15	
1977-05-29	02:57:00.01	49.9464	78.7717	5.75	3.09	
1977-06-29	03:07:00.35	49.9994	78.8667	5.20	2.51	
1978-06-11	02:57:00.08	49.9133	78.8019	5.83	3.11	
1978-07-05	02:46:59.97	49.9000	78.8667	5.77	3.10	
1979-02-01	04:13:00.17	50.0808	78.8533	5.29	2.84	
1984-03-29	05:19:10.66	49.9111	78.9269	5.86	3.25	
1984-04-25	01:09:05.99	49.9358	78.8506	5.90	3.27	76
1984-05-26	03:13:14.85	49.9789	79.0056	6.01	3.48	143
1984-07-14	01:09:12.99	49.9094	78.8772	6.10	3.43	
1984-10-27	01:50:12.93	49.9347	78.9281	6.19	3.40	
1984-12-02	03:19:08.85	50.0061	79.0089	5.77	3.30	
1984-12-16	03:55:05.07	49.9458	78.8086	6.12	3.39	
1984-12-28	03:50:13.09	49.8803	78.7039	6.00	3.34	113
1985-06-15	00:57:03.25	49.9086	78.8428	6.05	3.29	
1985-06-30	02:39:05.26	49.8644	78.6686	5.92	3.26	108
1985-07-20	00:53:16.91	49.9497	78.7839	5.89	3.28	
1987-03-12	01:57:19.57	49.9353	78.8289	5.31	2.61	11
1987-04-03	01:17:10.28	49.9181	78.7803	6.12	3.37	
1987-04-17	01:03:07.09	49.8778	78.6689	5.92	3.28	110
1987-06-20	00:53:07.09	49.9353	78.7442	6.03	3.34	
1987-08-02	00:58:09.27	49.8806	78.8747	5.83	3.24	80
1988-02-13	03:05:08.33	49.9367	78.8639	5.97	3.38	
1988-04-03	01:33:08.29	49.9083	78.9083	5.99	3.43	
1988-05-04	00:57:09.26	49.9494	78.7503	6.09	3.35	
1988-06-14	02:27:08.98	50.0189	78.9606	4.80	2.37	
1988-09-14	03:59:59.69	49.8778	78.8231	6.03	3.35	119
1988-11-12	03:30:06.26	50.0431	78.9689	5.24	2.74	
1988-12-17	04:18:09.29	49.8819	78.9247	5.83	3.19	
1989-01-22	03:57:09.02	49.9394	78.8194	6.10	3.27	
1989-02-12	04:15:09.34	49.9186	78.7111	5.86	3.19	
1989-07-08	03:47:00.03	49.8678	78.7803	5.55	2.85	33
1989-09-02	04:16:59.85	50.0058	78.9856	4.94	2.25	4
1989-10-19	09:49:59.81	49.9222	78.9083	5.86	3.19	75

The waveforms from most of the explosions are consistent, but there are some subtle differences. For instance, Sn phase from some explosions such as, 1979-02-01 and 1984-05-26, is stronger than those from other explorations as well as the Rg is less well excited on some explosions with smaller mb(P), such as 1976-04-21 and 1979-02-01. We calculated RMS Lg amplitude following the procedure given in Richards et al (1993) and Hansen et al. (1990). RMS Lg amplitude measurements for 37 explosions are compared with mb(P) given by Ringdal et al. (1992) in Figure 4. Regression of the measured RMS Lg values with mb(P) yields a standard deviation of 0.060 magnitude units and a slope of 0.89. We also compared the RMS Lg amplitude with a known yield of 11 UNEs as shown in Figure 4. The regression of RMS Lg amplitudes using BRV archive data with body-wave magnitudes or yields produced small scatter indicating that one may have confidence in both RMS Lg as a measure of source size, and in BRV archive instrument calibrations.

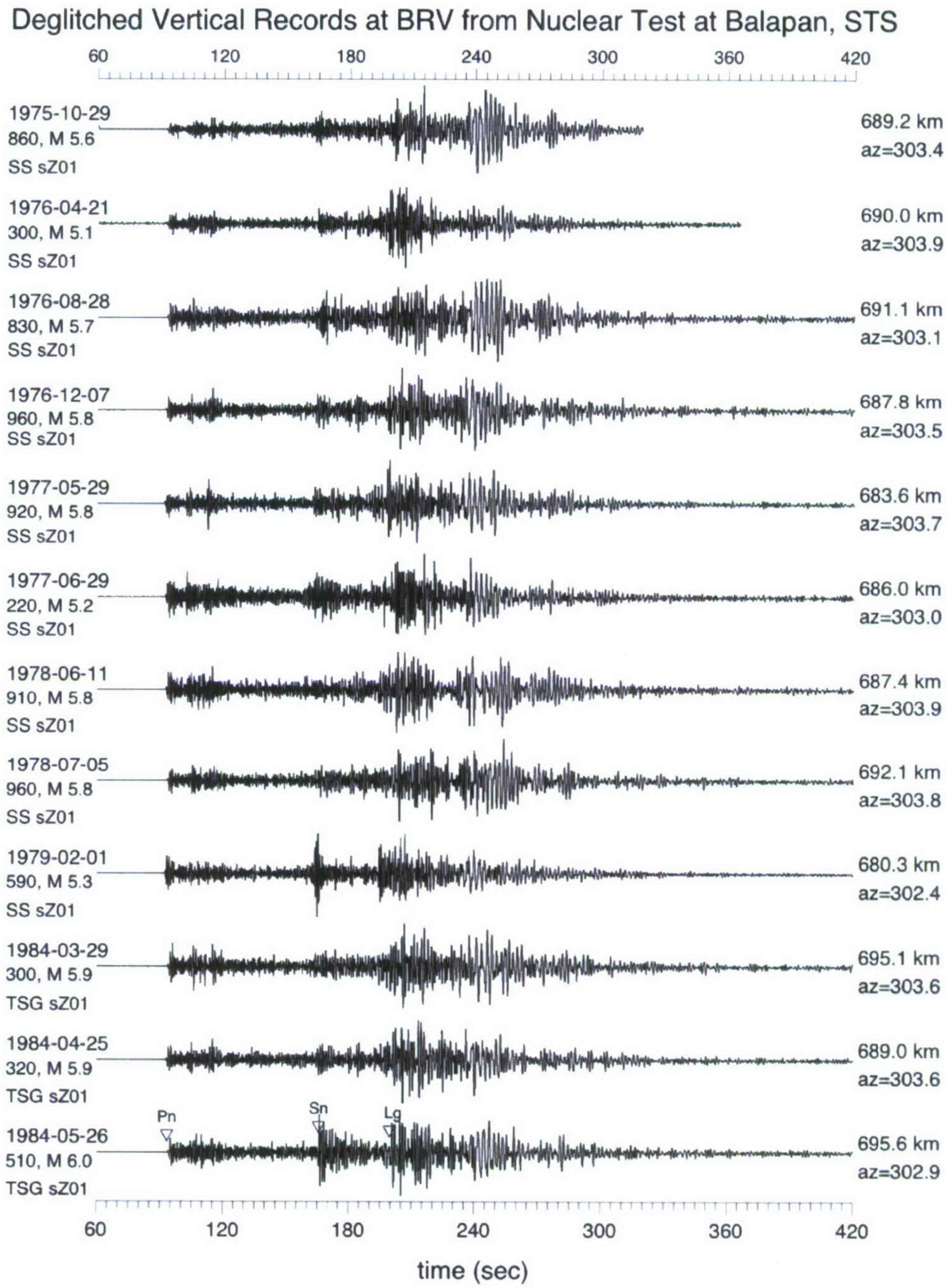

Figure 3. Examples of BRV archive seismograms recorded by SS-SKM-3 and TSG-KSVM systems. Explosion id, peak amplitude in integer digital counts, magnitude, mb(P), and recording system and channel names, are indicated at the beginning of each trace.

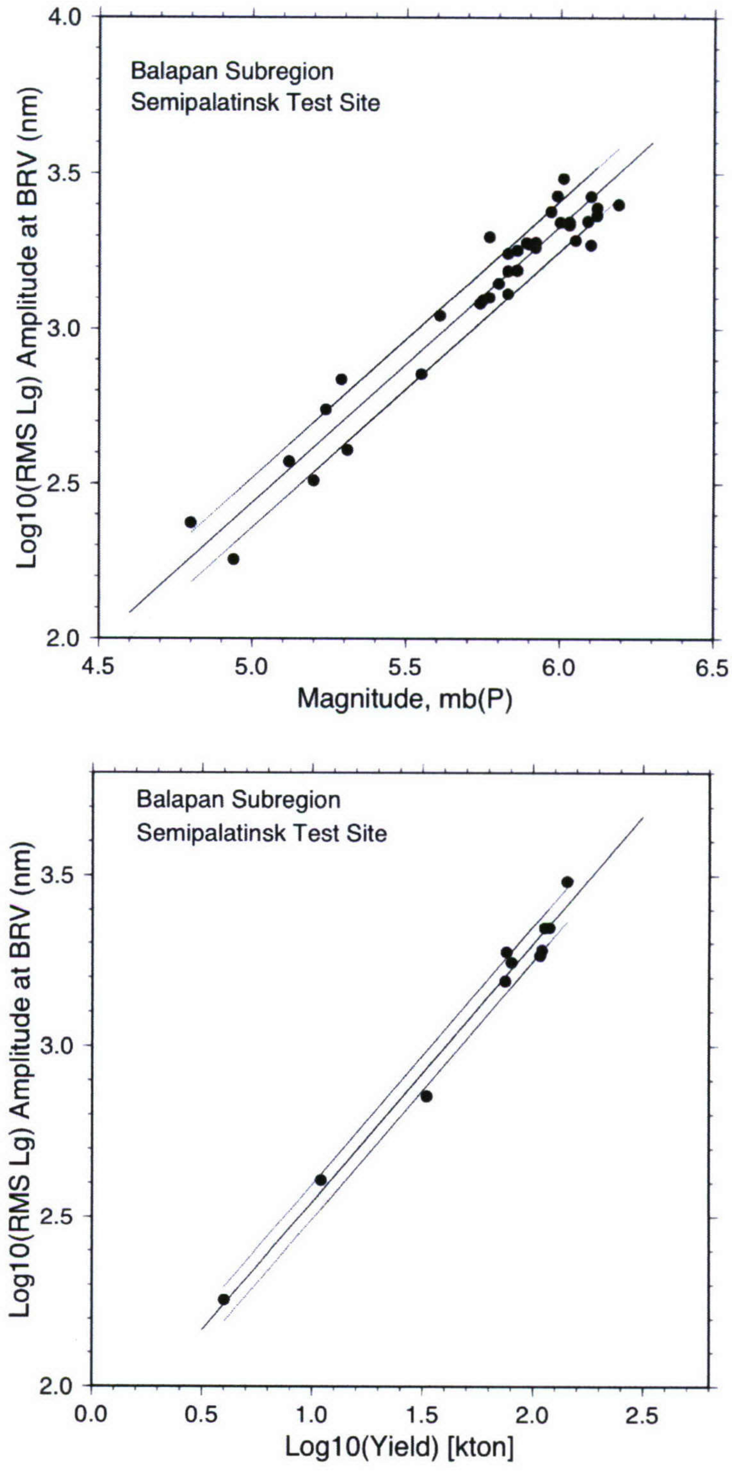

Figure 4. (Upper panel) Comparison of log10(RMS Lg) measurements in nm at BRV with body-wave magnitude mb(P). RMS Lg amplitudes are obtained from unfiltered data with a single gaussian window centered at an Lg group velocity of about 3.3 km/s. Solid line is a fitted slope of 0.89 and an orthogonal rms misfit of 0.060 magnitude units. The dotted lines correspond to ±2 S.D. (Lower panel) Comparison of log10(RMS Lg) measurements in nm at BRV with a reported yield in kilotons for 11 UNEs. Solid line is a fitted slope of 0.75 and an orthogonal rms misfit of 0.041 magnitude units. The dotted lines correspond to ±2 S.D.

Repeating Underground Nuclear Explosions?

Although UNEs may not be conducted at the same shaft except when two or more are carried out at almost the same time, two BRV archive records from nuclear tests at the Balapan subregion of STS are very similar (see Figure 5). However, the explosion on 1984-05-26 is a strong one with mb(P) = 6.01 and a reported yield of 143 kton, while the explosion on 1989-09-02 is a relatively weak one with mb(P) = 4.94 and a reported yield of 4 kton. Each of these two tests consisted of two separate explosive devices fired at almost the same time. The two records shown in Figure 5 have similar relative excitation of Pn, Sn, Lg, and Rg phases and are recorded by the same instrument at BRV.

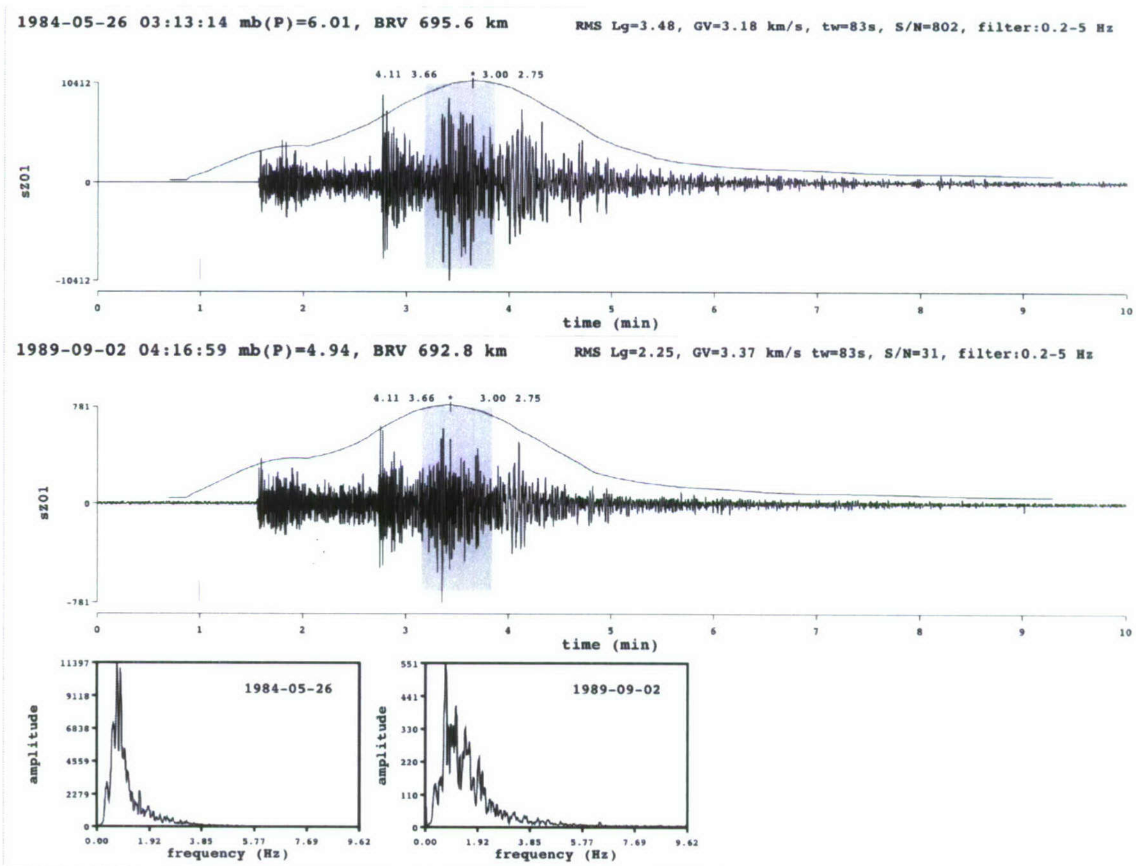

Figure 5. (top trace) vertical record from an underground nuclear test of two explosive devices on 1984-05-26 (mb(P) = 6.01). Mean squared amplitude trace is plotted above the unfiltered raw data and its maximum is indicated by a star. Shaded area indicates the width of gaussian window with $\pm\sigma$ = 20 s centered at the Lg group velocity of 3.3 km/s.
(middle panel) vertical record from an underground nuclear test on 1989-09-02 (mb(P) = 4.94). The shafts for these two tests are located about 2–3 km apart and have the same azimuth to BRV.
(bottom panel) spectra of the two seismograms as recorded at BRV.

Summary of Work Flow in this Project

We began this project with tar files for each of 350 underground nuclear tests in Eurasia from 1966 to 1996 containing the Borovoye digital seismogram archive, with glitches and lacking complete response information.

LANL processed regional signals for 210 nuclear tests (1,355 traces), mainly from the TSG system (but with some examples of SS and KOD records), prior to the beginning of this project. In 2007, LANL made this batch of already deglitched records available to Richards and Kim at Lamont.

In January 2008, LANL finished deglitching SS system waveforms from 148 tests (1215 traces), many of which had been recorded also on the TSG system, and this batch of waveforms was received at Lamont in February 2008.

In June 2008, LANL finished deglitching all the remaining waveforms in the SS and TSG systems (474 and 282 traces, respectively), and passed them along to Lamont in late June. These include records of nuclear tests at Novaya Zemlya. Figures above, in this paper, have used these deglitched records.

As of July 2008, there remain 709 traces recorded on the KOD system to be deglitched (by LANL) and to have their responses included (by Lamont). The KOD system is important as one of the very few digital datalogging systems in seismology in the 1960s and 1970s. It was first used in 1966 and ran continuously from 1967 to 1973. Information currently available to us on the response of this system is shown in Figure 6. We plan to make all of our processed waveforms openly available.

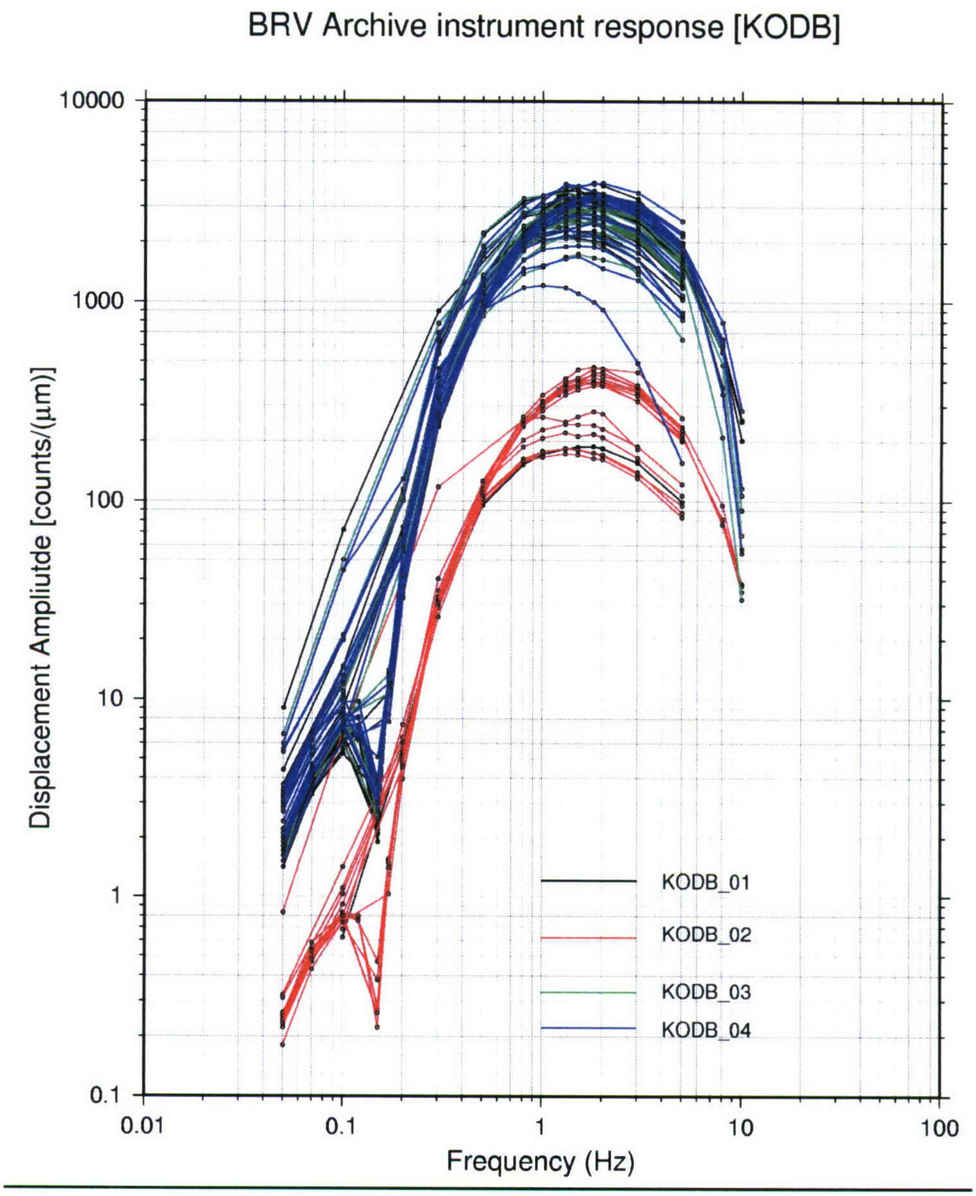

Figure 6. Responses of the KOD system, used at Borovoye Geophysical Observatory from 1966 to 1973. The notch filter, apparent in some of these sampled amplitude spectra (which were measured many times, leading to the numerous responses shown here), was designed to reduce the effect of microseisms.

CONCLUSIONS AND RECOMMENDATIONS

We are about halfway through this three-year project, which entails much tedious work in the effort to remove glitches and to establish confidence in our knowledge of instrument responses—some of them established as far back as forty years ago. We would not do such work without the prospect of seeing benefits in an improved understanding of issues that are important in nuclear explosion monitoring.

Research based on these data cannot be completed until the whole archive is processed. We expect such research to be carried out in the third year of this project.

Ongoing studies, likely to benefit from an improved Borovoye digital waveform archive (and that can also help ensure that we have the correct gains and responses), are as follows:

- Yield estimation, using RMS Lg, Rg, and coda.
- Effects of source depth and shot-point geology, for example using PNEs from different regions.
- Discrimination using spectral ratios of seismic signals from earthquakes and UNEs, for example, at the Semipalatinsk and Lop Nor test sites (in shafts and tunnels—which may impose their own slight differences on observed spectra).
- Discrimination between regional seismic signals of nuclear explosions and mining blasts of various types. (Note that mining blast signals are being routinely acquired today by the well-instrumented modem BRVK station.)

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